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Monitoring and moderating extreme indoor temperatures in low-income urban communities

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Abstract

Climate change presents significant threats to human health, especially for low-income urban communities in the Global South. Despite numerous studies of heat stress, surprisingly little is known about the temperatures actually encountered by people in their homes, or the benefits of affordable adaptations. This paper examines indoor air temperature measurements gathered from 47 living rooms within eight low-income communities of Accra and Tamale, Ghana. Using multiple temperature indices and a tiered analysis, we evaluate indoor temperature variations linked to roof type, ceiling insulation, presence of fans, and tree shade, for different housing types and locations. Our data reveal indoor temperatures in the range 22.4 °C to 45.9 °C for Accra, and 22.2 °C to 43.0 °C in Tamale. Using dummy regression analysis, we find that tree shade reduces the number of very hot days (>40 °C) and nights (>30 °C) by about 12 and 15 d per year, respectively. Building materials also strongly moderate indoor temperatures but in opposing ways: rooms with traditional mud walls and thatch roofs are on average 4.5 °C cooler than rooms in concrete block houses with uninsulated metal roofs during the day but are 1.5 °C warmer at night; rooms with ceiling insulation are on average 6.9 °C cooler in the day but 1.4 °C warmer at night. We conclude that sub-daily data are necessary for reporting extreme indoor temperatures, and that trade-offs between minimum and maximum temperatures require interventions to be assessed carefully before attempting to counter extreme heat inside homes.

1. Introduction

Millions of people are already exposed to deadly heat but this hazard is expected to become more frequent and severe as global temperatures rise (Zhao *et al* 2015, Nangombe *et al* 2018, Lie *et al* 2020). Populations in the tropics and subtropics are most likely to encounter the greatest rise in heatwaves with further warming (Dong *et al* 2015, Matthews *et al* 2017, Mora *et al* 2017, Rohat *et al* 2019, Raymond *et al* 2020). Moreover, high temperatures are exacerbated within dense cities by the urban heat island (UHI), which elevates heat stress compared to surrounding rural areas (Wilby 2007, Oleson *et al* 2015, Coffel *et al* 2017). Low-income communities are especially vulnerable given their relatively high exposure to extreme weather events and dependence on fragile water/energy infrastructure (Makaka and Meyer 2006, Maller and Strengers 2011, Ahmadalipour *et al* 2019, Gough *et al* 2019, Jagarnath *et al* 2020, Kayaga *et al* 2020). Hence, the global frontline for deadly heat is likely to be found in the densely populated informal settlements of the tropics in general, and sub-Saharan Africa in particular.

Table 1. Study settlements and their key characteristics.

City	Settlement	Code	Characteristics
Accra	Agbogbloshie	S	State-recognized indigenous settlement with dense infilling and busy informal market.
	Alajo	A	Large colonial style dwellings divided into multi-family units and informal compound housing.
	Odawna	O	Informal settlement located by Odaw river with busy market and various commercial activities.
	Bortianor	B	Peri-urban indigenous coastal settlement with relatively low housing density.
Tamale	Kukuo	K	Densely populated informal community with mix of modern and traditional housing.
	Lamashegu	L	Combined informal residential and industrial area.
	Gumani	G	Low-lying linear settlement.
	Ward K	W	Centrally located informal community.

Despite such concerns, surprisingly little is known about extreme indoor temperatures in urban areas (Scott *et al* 2017) and even less about affordable measures for lowering temperatures in homes within informal settlements of tropical Africa (Amos-Abanyie *et al* 2013, Dauda and Gao 2013). Exposure to high indoor temperatures matters because of the adverse impacts on human health, comfort, and productivity (Dapi *et al* 2010, White-Newsome *et al* 2012, Dunne *et al* 2013, Codjoe *et al* 2020). With more extreme temperatures and rapidly growing urban populations, there is mounting recognition that cities are priority places for climate action (Dodman *et al* 2019). More specifically, affordable/low-energy solutions are urgently needed to manage deadly heat, especially within low-income urban settlements in sub-Saharan Africa (Parkes *et al* 2019).

The effectiveness of building modifications to manage extreme temperatures depends on context. Many factors affect indoor temperatures, including: wall, roof and floor materials; roof pitch and reflectance, ventilation, size, and age of the structure; number of occupants and their behaviour; building use; artificial heat sources; building, window, and door size/orientation; site elevation, shade, local breezes, proximity to water bodies, and the urban heat island. Previous research has evaluated building age, window size/type, thermal mass or roof type using field measurements and/or building simulations (Taylor *et al* 2000, Amos-Abanyie *et al* 2013, Morakinyo *et al* 2016, Naicker *et al* 2017, Wright *et al* 2017, Ayanlade *et al* 2019). Many studies use daily *mean* temperatures even though averages can obscure critical variations within the diel (24 h) thermal regime. Other research draws on qualitative evidence (e.g. Nematchoua *et al* 2014, 2017) or multi-variate indices of thermal comfort and heat stress (e.g. Holmes *et al* 2016). Metrics of human thermoregulation combine permutations of environmental data (such as air temperature, humidity, air speed and radiant energy) with information about occupants' metabolic rate and clothing. Dry-bulb air temperature features in the majority of heat warning systems and building energy models.

In this paper, we advance understanding by statistically relating building types and modifications to sub-hourly air temperature variations monitored in diverse homes within low-income urban communities. Temperatures were studied in two cities in Ghana, namely: Accra (5°33′ N, 0°12′ W, population 4.2 million, hot semi-arid/tropical wet climate) and Tamale (9°24′ N, 0°51′ W, population 0.4 million, tropical wet and dry climate). These communities and cities were chosen because they regularly endure adverse impacts from extreme heat (Gough *et al* 2019, Codjoe *et al* 2020)—events that have become more frequent and severe in recent decades (Ringard *et al* 2016). The following analysis provides evidence of the efficacy of affordable measures intended to moderate extreme indoor temperatures.

2. Data and methods

2.1. Field data

Four communities were chosen in Acca and four more in Tamale based on their mix of building types and density, informality, and vulnerability to extreme heat (table 1). *Tinytag Transit 2* thermistors were installed within homes to monitor air temperatures encountered by occupants during 2018. According to the manufacturer, the sensors have a precision of 0.01 °C and accuracy of 0.4 °C in the range 0 °C to 50 °C (Gemini Data Loggers 2015). The logging interval was set to 10 min.

Homes were selected to represent different structures, building materials, sizes, and locations (figure 1). This process was guided by the local knowledge of 'community champions' (residents nominated by their communities to liaise between households and the research team). A standard form captured information about building location (coordinates, elevation), number of floors and building height (as a proxy for size/thermal mass), alongside other characteristics (wall, and roof materials, number of doors and windows, amount of shade, and orientation). Any modifications to

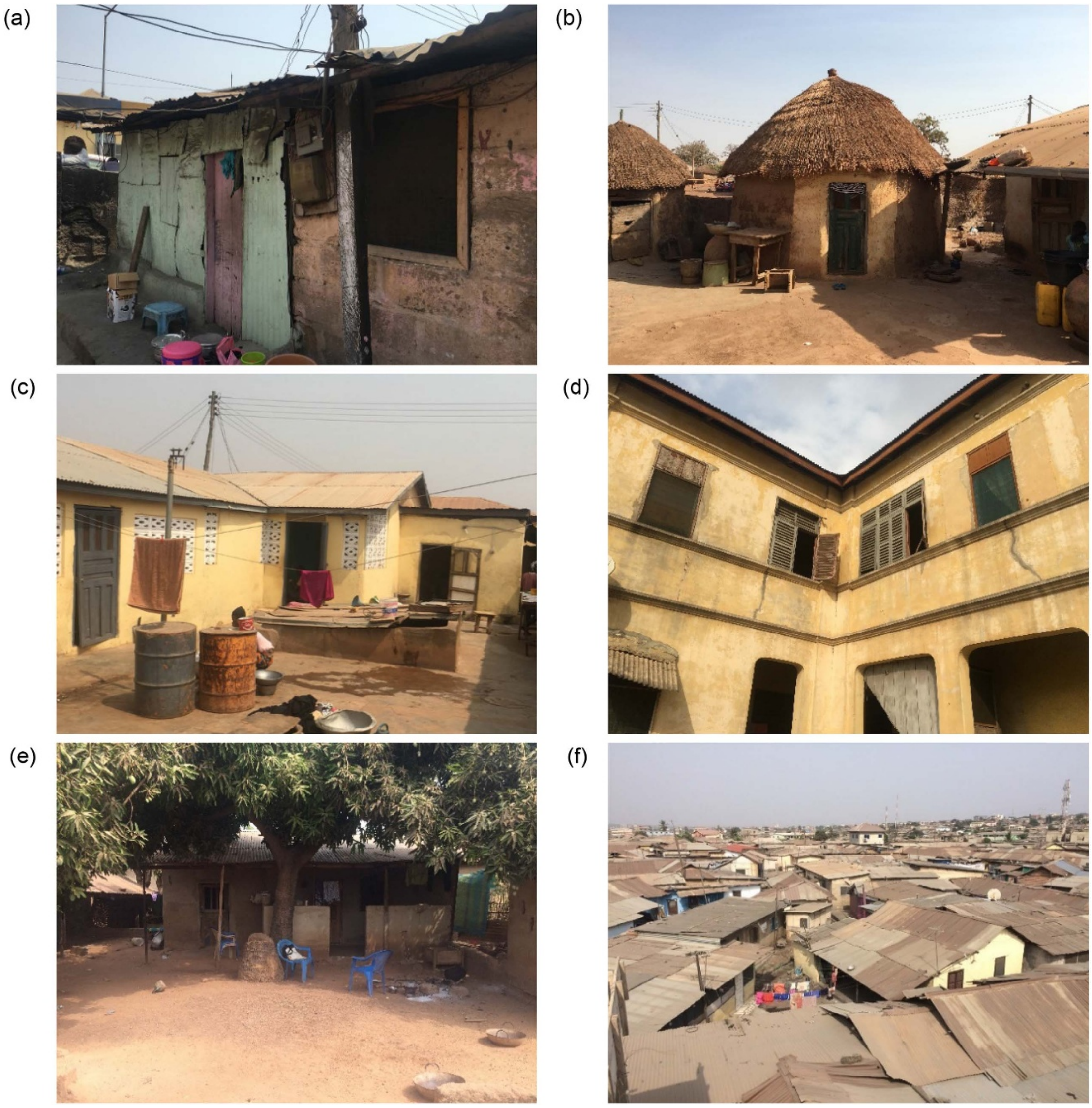

Figure 1. Example dwellings with: (a) wood walls and sheet metal-roof (Accra); (b) traditional mud walls and thatch roof (Tamale); (c) single-storey concrete block walls and sheet metal roof (Tamale); (d) two-storey/large concrete block walls (Accra); (e) some shade (Tamale); and (f) no shade (Accra).

counter high temperatures, such as ceiling insulation (plywood, plastic sheeting, Polyvinyl chloride, a synthetic plastic polymer tongue and groove panels, plaster), fans (ceiling, free-standing), tree shade or air conditioning, were also recorded. Room occupancy, usage, and artificial heat sources were noted too.

At each home, one thermistor was fixed outdoors on a self-shaded north-facing wall to measure ambient air temperature, whilst up to four were sited inside rooms with various ceiling types, usage, occupancy, and dimensions (figure S1 (available online at stacks.iop.org/ERL/16/024033/mmedia)). All thermistors were mounted ∼2 m above ground level, away from direct sunlight and artificial heat sources. These sites had to be as unobtrusive as possible and always beyond the reach of children. Spot measurements were taken within several homes to assess any height-dependency of air temperatures using a Testo 610 handheld sensor (Testo 2020). Variations in temperature were always smaller than instrument accuracy (±0.5 °C).

Thermistors were also installed within Stevenson screens at ∼1.25 m above ground level alongside thermometers operated by the Ghana Meteorological Agency (GMA) at three sites: (A) their compound on the University of Ghana (Legon, Accra) campus, (B) Accra airport, and (C) Tamale airport (figure S1). Indoor temperatures are expected to differ from these records because a key purpose of a dwelling is to regulate the thermal environment for occupants. Nonetheless, previous studies show strong positive linear associations between indoor and outdoor temperatures on a home-by-home basis (e.g. Quinn *et al* 2014, Nguyen and Dockery 2016, Naicker *et al* 2017). Here, our thermistor records at GMA stations (A and C above) are used as points of reference for our outdoor and indoor temperature measurements. Sensors

Table 2. Definitions of primary (daily) and derived (from daily) temperature indices obtained for each sensor site.

Code	Description	Units
	Primary indices (daily)	
Tn	Daily minimum temperature	°C
Tx	Daily maximum temperature	°C
Tm	Daily mean temperature	°C
DTR	Daily temperature range (Tx—Tn)	°C
	Derived indices (from daily)	
Tn30C	Number of hot nights (Tn > 30 °C)	days
Tx40C	Number of very hot days (Tx > 40 °C)	days
Tnn	Minimum value of daily Tn	°C
Tn01p	1st percentile of daily Tn	°C
Tn10p	10th percentile of daily Tn	°C
Tn50p	Median (50th percentile) of daily Tn	°C
Tnx	Maximum value of daily Tn	°C
Txn	Minimum value of daily Tx	°C
Tx50p	Median (50th percentile) of daily Tx	°C
Tx90p	90th percentile of daily Tx	°C
Tx99p	99th percentile of daily Tx	°C
Txx	Maximum value of daily Tx	°C

housed within these official meteorological stations are expected to have more stable environments than outdoor sites within communities.

Initially, a network of 96 thermistors were deployed; after 1 year, 81 were still in place and operating (47 inside homes, 24 outside homes, plus 7 verandas, and 3 at meteorological stations). Data were downloaded every other month and quality assured. Day-to-day changes and basic range checks were performed, with records from GMA stations and homes cross-compared to eliminate outliers/suspect values associated with artificial heat exposure. Percentile-based indicators, rather than absolute extremes, were used for statistical analysis (section 2.3) to reduce possible contamination by erroneous outliers. Abrupt changes in the daily range helped to detect any relocation or tampering with a sensor. The cleaned archive yielded more than 3.5 million data values for analysis. Importantly, the high temporal resolution enabled evaluation of temperature variations within a day, so the effects of location and building factors can be discerned from a range of temperature metrics.

According to multi-decadal thermometer-based records provided by GMA (for sites B and C above), annual mean temperatures in Tamale and Accra for 2018 were 9th and 11th highest since 1960, respectively. Since the 1960s, annual mean temperatures rose by 0.26 °C decade^{-1} and 0.18 °C decade^{-1} at the same sites. Hence, we regard our study period as representative of the generally warmer conditions experienced in recent decades. Hereafter, we present results from thermistor data gathered during the 365 d period covering 22 January 2018–21 January 2019.

2.2. Primary and derived temperature indices

Primary series of daily minimum (Tn), daily maximum (Tx), daily mean (Tm), and daily range of temperature (DTR; Tx minus Tn) were obtained from thermistor recordings at each site (table 2). These data were then used to derive 12 temperature indices, again for each site. These are the number of very hot nights [when Tn > 30 °C] (Tn30C); the number of very hot days [when Tx > 40 °C] (Tx40C); temperature minima summarised by the very lowest (Tnn), the 1st (Tn01p), 10th (Tn10p), and 50th (Tn50p) percentile, and very highest (Tnx) of the daily distribution of Tn; temperature maxima characterised by the very lowest (Txn), the 50th (Tx50p), 90th (Tx90p) and 99th (Tx99p) percentile, and the very highest (Txx) of the daily distribution of Tx. Note that the temperature thresholds for Tn30C and Tx40C are higher than used elsewhere because the conventional definition of a 'tropical night' (Tn > 20 °C) (Sillmann *et al* 2013) would be exceeded 100% of the time at all sites (except for the GMA station in Tamale).

2.3. Statistical analysis

We used the above indices to discern variations in temperature associated with building location, type, and modifications that favour lower indoor temperatures. Three tiers of statistical technique were applied: (a) community level averaging of temperature to evaluate local variations in the strength of the UHI; (b) category level averages to show differences in temperature between groups of similar buildings; and (c) building level dummy regression analysis of variables influencing selected indoor temperature indices.

For tier 1, mean daily indoor and outdoor temperatures were stratified by community then compared with thermistor data from GMA sites (A and C). Since these meteorological stations are in open-grassed sites outside the city centre, differences in temperature between them and communities are indicative of local UHI intensity. This reveals ambient temperature variations across each city reflecting local building density, artificial heat sources, proximity to open/green space, water bodies, and distance from the coast (for Accra).

For tier 2, building types were categorized by height/number of floors, wall, and roof material as well as by measures intended to reduce indoor temperatures (table S1). The sampled housing archetypes were as follows. Single-storey homes (⩽5 m high) were comprised of wood walls with metal or asbestos sheet roofs (figure 1(a)), or traditional mud walls with thatch roofs (figure 1(b)), or concrete walls with metal or asbestos roofs (figure 1(c)). Two-storey or large (>5 m high) buildings had concrete walls and asbestos sheet or tiled roofs (figure 1(d)). Shade by vegetation was classified as either present (figure 1(e)) or absent (figure 1(f)). This binary approach was justified given that rapid visual assessment of shade is problematic due to variations by time of day and effect of neighbouring structures.

Building-specific indices (Tn10p, Tx90p and mean Tm) were stratified by city, then averaged by housing archetype, or cooling measure. Two-sample *t*-tests of differences in the mean (assuming unequal variance) were applied to the groups of data. For example, indoor temperatures may be compared for sub-samples of single-storey (n_1) and two-storey (n_2) housing in Accra, with the null hypothesis of no difference. The number of degrees of freedom ($n_1 + n_2 - 2$) is sometimes small, in which case the statistical power to identify differences between factors is limited (i.e. there is a higher chance of accepting a null hypothesis that is actually false). Indoor temperatures were also compared for rooms with different modifications within the same house or with a nearby property of similar size, age, and design. Resulting scatterplots reveal daily variations of indoor Tx and Tn depending on outdoor temperatures (at the reference site); roof type (metal versus thatch); ceiling type (insulated versus uninsulated); shade (tree cover versus unshaded); and fans (present or absent).

For tier 3, we apply dummy regression modelling to *i* temperature indices (Tn30C, Tx40C, Tn10p, Tm, and Tx90p) to quantify the benefit of modifications relative to the effects of building location and characteristics. The influence of *n* dummy variables (v_j) were estimated from the coefficients of the following model, fitted via ordinary least squares:

$$T_i = \alpha_i + \sum_{j=1}^{n} \beta_{i,j} v_j + e_i \quad (1)$$

where T_i is the indoor temperature index, α_i is the model intercept, $\beta_{i,j}$ are the model coefficients, and e_i is the model error. Eight dummy variables were applied, each coded either 0 for the reference case or 1 for the 'treatment' (table S2). The variables were city (0 for Tamale); coastal (0 for sites > 1 km from the sea); thermal mass (0 for buildings ⩽ 5 m high); wall material (0 for wood); roof material (0 for sheet metal or asbestos); ceiling insulation (0 for none); tree shade (0 for none); and ceiling or free-standing fan (0 for none). The coefficients $\beta_{i,j}$ are directly comparable (in each temperature index). Some dummy variables could have been sub-classified, such as ceiling insulation (by material), tree shade (by extent), or sheet roofing (by material). However, there is a danger of over-fitting the model given the modest sample size (45 rooms after excluding two homes with air conditioning). The dummy variables allowed us to pool temperature indices reflecting very different building types and locations.

3. Results

3.1. Variations in extreme temperature between sites

Our thermistor data reveal considerable variations of indoor temperature linked to site. In Accra, the lowest recorded indoor temperature (Tn) was 22.4 °C for a small asbestos-roofed, wood-walled room near the coast; the highest indoor temperature (Tx) was 45.9 °C for a small metal-roofed, wood-walled room in a densely built-up area. As expected, equivalent values (Tn = 20.7 °C, Tx = 37.0 °C) at Accra meteorological station were lower. The average number of very hot nights (Tn30C) within homes ranged between 7 (single-storey concrete houses) and 92 (two-storey or large concrete houses) per year, whereas none were recorded at the meteorological station (table 3). Likewise, the number of very hot days (Tx40C) was on average 40 inside single-storey wood homes but zero at the nearest meteorological station.

In Tamale, the lowest indoor temperature (Tn) was 22.2 °C and the highest (Tx) was 43.0 °C (both for metal-roofed homes). Temperatures at Tamale airport ranged between 17.4 °C and 41.4 °C. Average Tn30C within metal and thatch roof homes were 96 and 102 nights per year respectively, compared with none at the GMA station (table 3). In contrast, average Tx40C was zero in thatch roof rooms, 7 in metal roof rooms, and 10 at the GMA station.

We also stratified our temperature data by community to elucidate variations across the two cities. In Accra, average indoor Tn were higher for all communities than at GMA stations (by up to +3.3 °C in Alajo) (figure 2). Likewise, indoor Tx was higher in all communities (by up to +3.1 °C in Alajo) except Odawna (−0.7 °C), an area with some two-storey houses (figure 1(d)). In Tamale, Tn were higher than the GMA station in all communities, whereas Tx were lower on average than the meteorological station (by as much as −1.3 °C in Ward K).

Outdoor temperatures in communities were consistently higher than those at GMA stations (figure 2), as official sites (A and C) are located away from the city centre, in open, well-ventilated areas. Hence, by comparing outdoor temperature differences between communities and reference stations, we estimated

Table 3. Arithmetic mean temperature indices based on the same from each site, pooled by building category and city. Single-storey houses are distinguished by wall material (in parentheses). Mean temperature indices are also given for outdoor (self-shaded) sites within communities and at reference meteorological stations. Refer to table 2 for index definitions.

City	Category	*n*	Tm (°C)	DTR (°C)	Tn30C (days)	Tx40C (days)	Tnn (°C)	Tn01p (°C)	Tn10p (°C)	Tn50p (°C)	Tnx (°C)	Txn (°C)	Tx50p (°C)	Tx90p (°C)	Tx99p (°C)	Txx (°C)
Accra (*n* = 33)	Single-storey (wood)	7	31.9	8.5	28	40	24.0	24.9	26.0	27.8	29.9	28.6	36.6	38.5	39.5	40.2
	Single-storey (concrete)	5	29.2	4.5	7	0	23.9	24.6	25.5	27.1	29.8	26.8	31.8	33.2	34.5	35.1
	Two-storey/large (concrete)	6	30.0	1.8	92	0	26.2	26.7	27.5	29.2	31.2	27.7	31.2	32.5	33.3	33.7
	Veranda	1	30.3	10.1	0	1	21.7	21.9	23.5	25.4	27.6	27.1	35.9	37.4	38.4	40.0
	Outdoor (self-shaded)	13	31.0	9.4	0	36	22.2	23.0	24.6	26.4	28.7	27.9	36.0	38.6	40.1	40.9
	Met site	1	28.2	7.3	0	0	20.7	21.6	22.9	24.6	27.4	25.0	32.1	34.3	35.6	37.0
Tamale (*n* = 48)	Single-storey (mud)	6	30.8	3.8	102	0	25.1	25.7	26.9	28.6	32.9	27.6	32.7	35.4	36.8	37.4
	Single-storey (concrete)	23	31.3	5.5	96	7	24.8	25.3	26.3	28.3	33.1	27.6	34.0	37.5	38.7	39.2
	Veranda	6	30.9	10.5	22	57	21.5	22.0	23.2	25.5	30.4	26.3	36.6	40.2	42.2	43.0
	Outdoor (self-shaded)	11	31.0	11.0	3	59	20.7	21.3	22.7	25.2	30.4	26.0	36.5	40.5	42.1	42.9
	Met site	2	29.0	11.2	0	10	17.4	18.2	20.2	23.4	29.1	24.6	35.3	39.0	40.5	41.4

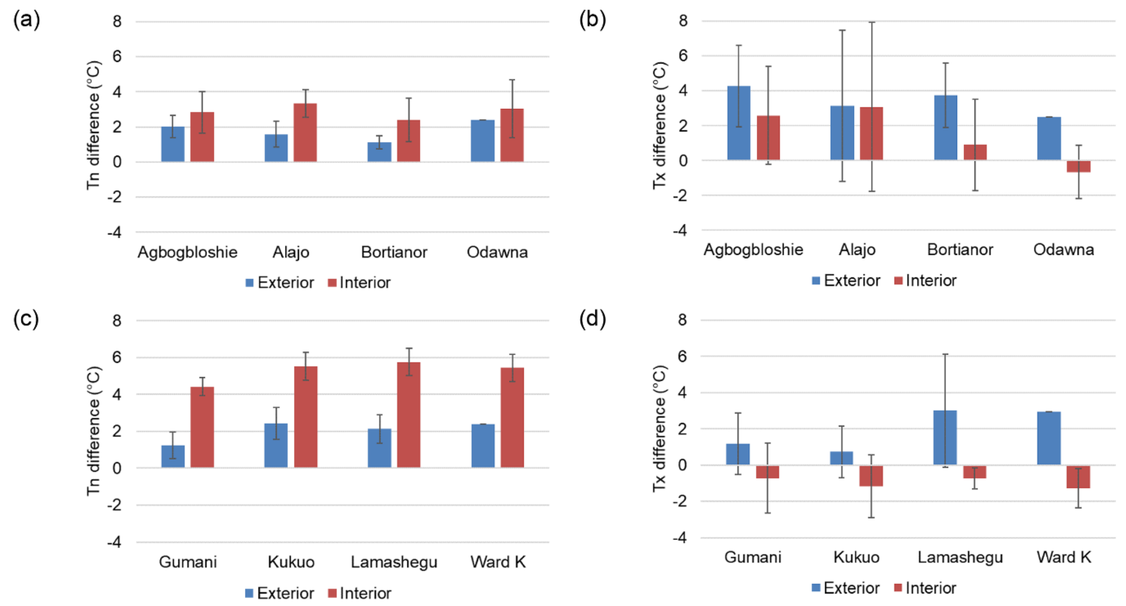

Figure 2. Difference in daily mean (a), (c) minimum temperature (Tn) and (b), (d) maximum temperature (Tx) within living rooms (interior) and outside homes (exterior) by community in (a), (b) Accra and (c), (d) Tamale, compared with reference meteorological stations. T-bars denote one standard deviation from the mean.

Table 4. Differences in indoor temperature indices associated with building characteristics and modifications, based on two-sample *t*-tests assuming unequal variance. The number of degrees of freedom (df) are also given. Rooms with air conditioning were excluded.

City	Factors	df	Tn10p (°C)	Tm (°C)	Tx90p (°C)
Accra	Two-storey/large house *v* single-storey house	14	**+1.5**‡	**−1.2**†	**−4.4**‡
	Insulated room *v* uninsulated room	14	**+1.4**†	**−2.3**†	**−6.9**‡
	Some shade *v* no shade	14	−0.2	−0.5	−0.7
	Fan *v* no fan	14	+0.4	+0.3	−0.2
Tamale	Thatch roof *v* metal roof	27	+0.6	**−0.6***	**−2.2**‡
	Insulated roof *v* uninsulated roof	27	+0.4	−0.2	−0.7
	Insulated metal roof *v* uninsulated metal roof	21	+1.1	**−0.8***	**−2.8**†
	Insulated thatch roof *v* uninsulated thatch roof	4	−0.1	+0.1	0
	Insulated thatch roof *v* uninsulated metal roof	6	+1.5	**−1.2**†	**−4.5**‡
	Insulated thatch roof *v* insulated metal roof	19	+0.3	**−0.4**†	−1.6
	Uninsulated thatch roof *v* insulated metal roof	21	+0.4	−0.5	**−1.7**‡
	Some shade *v* no shade	27	**−0.8***	**−0.7**†	−0.4
	Fan *v* no fan	27	0	0.5	**+1.3***

Significant differences are shown in **bold** for *p*-values: *<0.10, †<0.05, ‡<0.01.

local UHI intensity. Ambient Tx (i.e. daytime UHI) in communities were on average +2.5 to +4.3 °C higher in Accra and +0.7 to +3.0 °C higher in Tamale. Outdoor Tn (i.e. night-time UHI) in communities differed from reference sites by +1.1 °C to +2.4 °C in Accra, and by +1.2 °C to +2.4 °C in Tamale. These findings are consistent with previous studies of UHIs in tropical Africa (Ojeh *et al* 2016, Giridharan and Emmanuel 2018, Simwanda *et al* 2019).

3.2. Variations in temperature extremes between and within building types

Home type and community-level averages mask considerable temperature variations between and within building archetypes, especially during very hot days and nights. Such differences are generally obscured by daily mean statistics (table 4). In Accra, significant ($p < 0.01$) variations were found in high indoor temperatures (Tx90p) between rooms with and without ceiling insulation (−6.9 °C). Rooms in two-story residences were also significantly cooler on average than those in single-storey homes (−4.4 °C). However, night temperatures (Tn10p) were higher in insulated versus uninsulated rooms (+1.4 °C) and in two- versus single-storey homes (+1.5 °C). The effect of shade (−0.2 °C) or fans (+0.4 °C) was insignificant ($p > 0.1$). In Tamale, the largest difference in Tx90p was between homes with insulated thatch roofs compared with uninsulated metal roofs (−4.5 °C) (table 4). Similarly, Tx90p was lower in rooms with insulated ceilings (−2.8 °C). Overall, rooms with thatch roofs had lower Tx90p than those with metal roofs (−2.2 °C) but only marginally lower Tm (−0.6 °C). There were weakly significant ($p < 0.1$)

differences in Tn10p (−0.8 °C) for shaded rooms and in Tx90p (+1.3 °C) for rooms with fans.

Differences also emerge when comparing daily Tx (−4.9 °C) and Tn (+1.3 °C) for rooms with thatch or metal roofs, in this case, within the same house (figures 3(a) and (b)). During the hottest day sampled in Tamale, the smallest daily temperature range was recorded in a room with thatch underlain by plastic sheeting (installed to protect occupants from dust and insects rather than for insulation) (figure 4(a)). Variations within the diel regime were likewise recorded amongst rooms with metal roofs (figure 4(b)). The room with the smallest daily variation was in a large, single-storey house inhabited by one family, with partial shade to the rear and PVC cladding on high ceilings. Conversely, the metal-roofed room with greatest daily temperature range had no shade and a low, uninsulated ceiling.

Similarly, diel temperature profiles for the hottest day in Accra were different for single-storey houses with insulated ceilings compared to those with uninsulated ceilings (figure 4(c)). The sample size is not large enough to discern the effect of floor-level (in two-storey buildings) or roof type; however, the data reveal a narrower indoor daily temperature range for insulated than uninsulated rooms, with a diel regime similar to thatch (figure 4(a)). Although Tx was lower, temperatures in rooms with insulated metal/asbestos and thatch roofs were consistently higher at night than uninsulated metal-roofed rooms (see below).

3.3. Effect of individual modifications on indoor temperatures

Modifications to homes, such as ceiling insulation, shade, and fans are intended to improve thermal comfort. However, consequences for indoor temperatures were mixed, depending on time of day and building archetype. Rooms with insulated ceilings were up to 7 °C cooler in the day than ones without insulated ceilings within the same home (figures 3(c) and (d)) but during one night, the insulated room did not fall below 32.2 °C. Hence, insulation reduces Tx but at the penalty of higher Tn.

Tree shade reduces indoor temperatures most during the day (Tx) in the dry season (figure S2(a)) and, as expected, there is no difference between shaded and unshaded rooms at night (figure S2(b)). Although lower indoor temperatures were recorded in rooms with some shade (table 4), the difference in Tx peaked during April–July (2.2 °C) for the two exemplar rooms. On some days, Tx in a shaded room was at least 8 °C cooler than the meteorological station (figure 3(e)).

Discerning the effect of (ceiling) fans on indoor temperatures is problematic as their presence or absence tends to coincide with that of insulation. Moreover, even when present, fans may not be used. Overall, fans are not expected to reduce indoor temperatures unless by promoting ventilation of cooler air from outside. This was confirmed by the absence of any statistically significant temperature differences in our pairwise analysis of all rooms with, and without fans (table 4). Likewise, there was no differences in temperature due to fans in the subset of rooms with no ceiling insulation (figure S3). Although Tn was higher in some rooms with PVC ceiling cladding and a fan (figures 3(g) and (h)), this may be explained by a greater number of electrical appliances (i.e. artificial heat sources) and fewer doors.

3.4. Combined effects of modifications on indoor temperatures

We used dummy regression to evaluate the relative effects of geographic location (city, distance from sea), building archetype (number of floors/ thermal mass, wall, and roof materials), and modifications (ceiling insulation, tree shade, and fans) on indoor temperature indices (figure 5 and table S2). The amount of variance explained by these factors ranged from 17% (Tx40C) to 73% (Tx90p). Statistically significant (p = 0.05) model coefficients (with standard errors) emerge for rooms with:

(a) Thatch roof versus metal roof. This changes Tx40C by −38 (±19) d, Tm by −1.0 (±0.4) °C, Tn10p by +1.0 (±0.4) °C, and Tx90p by −3.7 (±0.8) °C.
(b) Ceiling insulation versus no insulation. This changes Tm by −0.8 (±0.3) °C and Tx90p by −2.6 (±0.6) °C.
(c) Concrete/mud walls versus wood walls. This changes Tx90p by −2.3 (±1.0) °C.
(d) Tree shade versus no shade. This changes Tn10p by −0.7 (±0.3) °C.
(e) Large (>5 m high) versus small (⩽5 m high) buildings. This changes Tx90p by −2.6 (±1.0) °C.

Dummy variable coefficients can be summed to give combined effects of several measures. For example, traditional homes in Tamale are always ⩽5 m high, have thatch roofs and mud walls but are not located by the coast. Hence, to reduce Tx90p in such homes, the modelled measures (i.e. ceiling insulation −2.6 °C, tree shade −0.1 °C, and a fan −0.2 °C) would yield a benefit of −2.9 °C relative to the reference building (table S2). However, the model also indicates that this set of modifications would increase the number of very hot nights by 28 per year. Adding ceiling insulation, tree shade and a fan to a concrete walled and metal roofed home would change Tx90p by +0.8 °C and Tn30C by −7 nights per year.

Day/night trade-offs are also predicted by the models for modifications to low-income homes in Accra. For example, upgrading a reference building

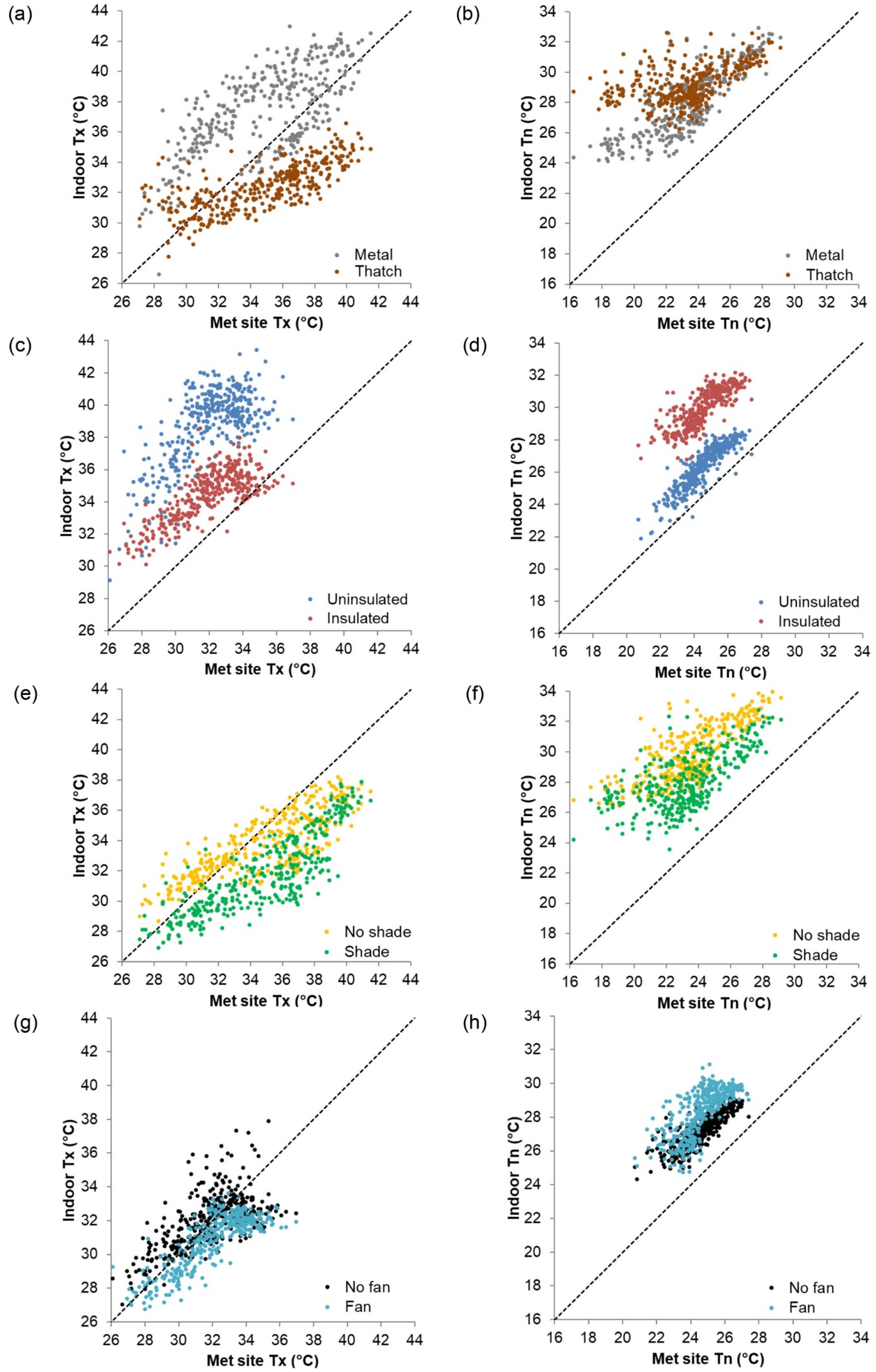

Figure 3. Indoor daily maximum (Tx) and minimum (Tn) temperatures for different rooms with (a), (b) metal or thatched roofs; (c), (d) uninsulated or insulated ceilings; (e), (f) without or with shade; and (g), (h) without or with ceiling fans. Dashed lines are the 1:1 relationship between indoor and reference station temperatures.

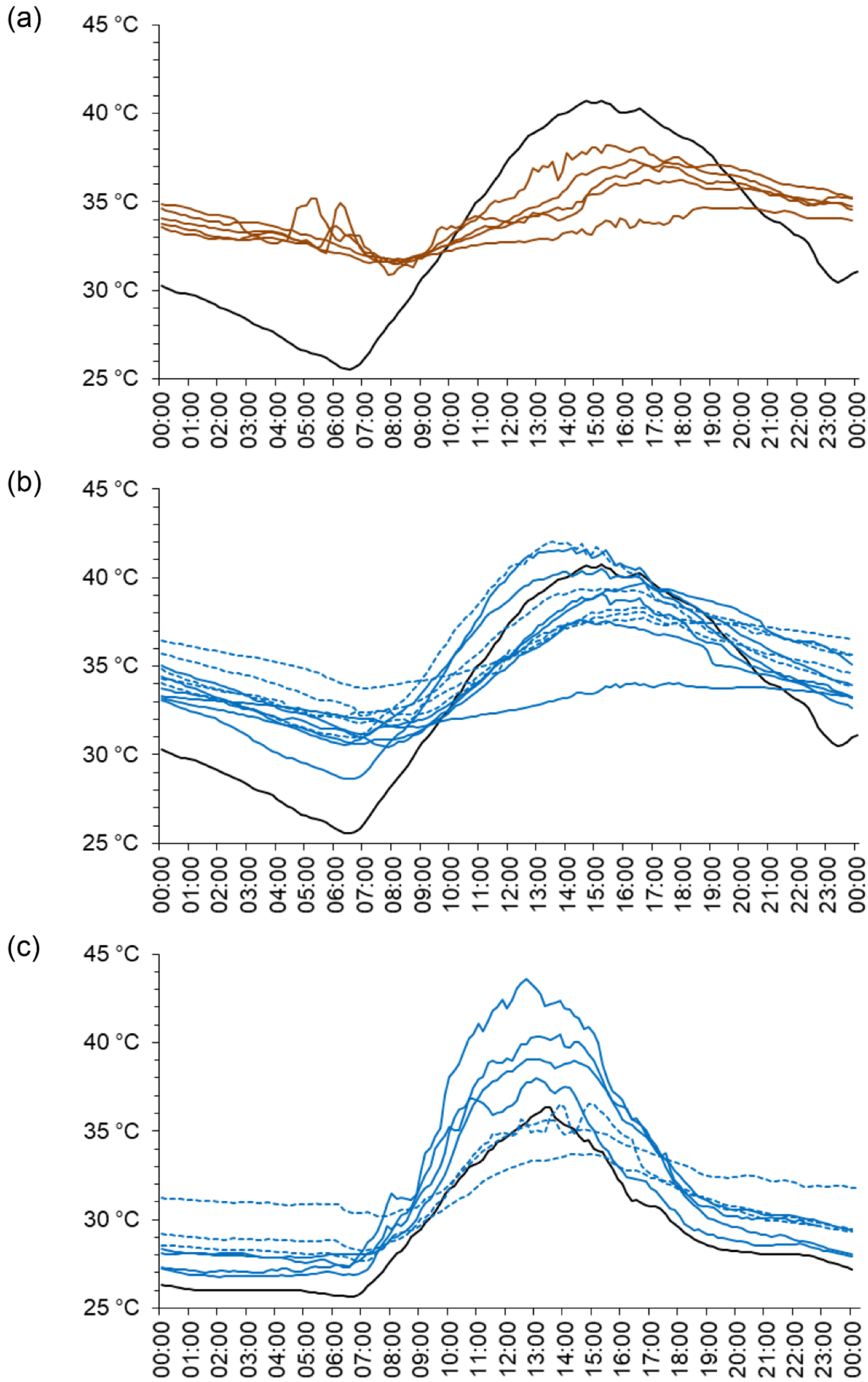

Figure 4. Indoor temperatures on the hottest days of the study period in Tamale (3 March 2018) for single-storey houses with (a) thatch (brown lines); (b) metal (blue lines, Kukuo dashed, Gumani solid) and; in Accra (25 February 2018) for (c) metal/asbestos roofs (blue lines, where insulated are dashed; uninsulated are solid). Temperatures at the reference meteorological station are also shown (black lines).

(⩽5 m high, wooden wall, metal roof, with no insulation) to one with concrete walls, insulation, and fan, could change Tx90p by −5.2 °C but Tn30C by +57 nights per year. Overall, choice of roof material and ceiling insulation are the most heavily weighted variables for reducing Tx90p. Addition of tree shade reduces the frequency of hot nights by 15 per year.

4. Discussion

Relatively little is known about indoor temperatures in tropical Africa; even less for those living and working within high-density, informal communities. In this paper we have shown that building materials and modifications can have significant impacts on the indoor temperatures endured by residents

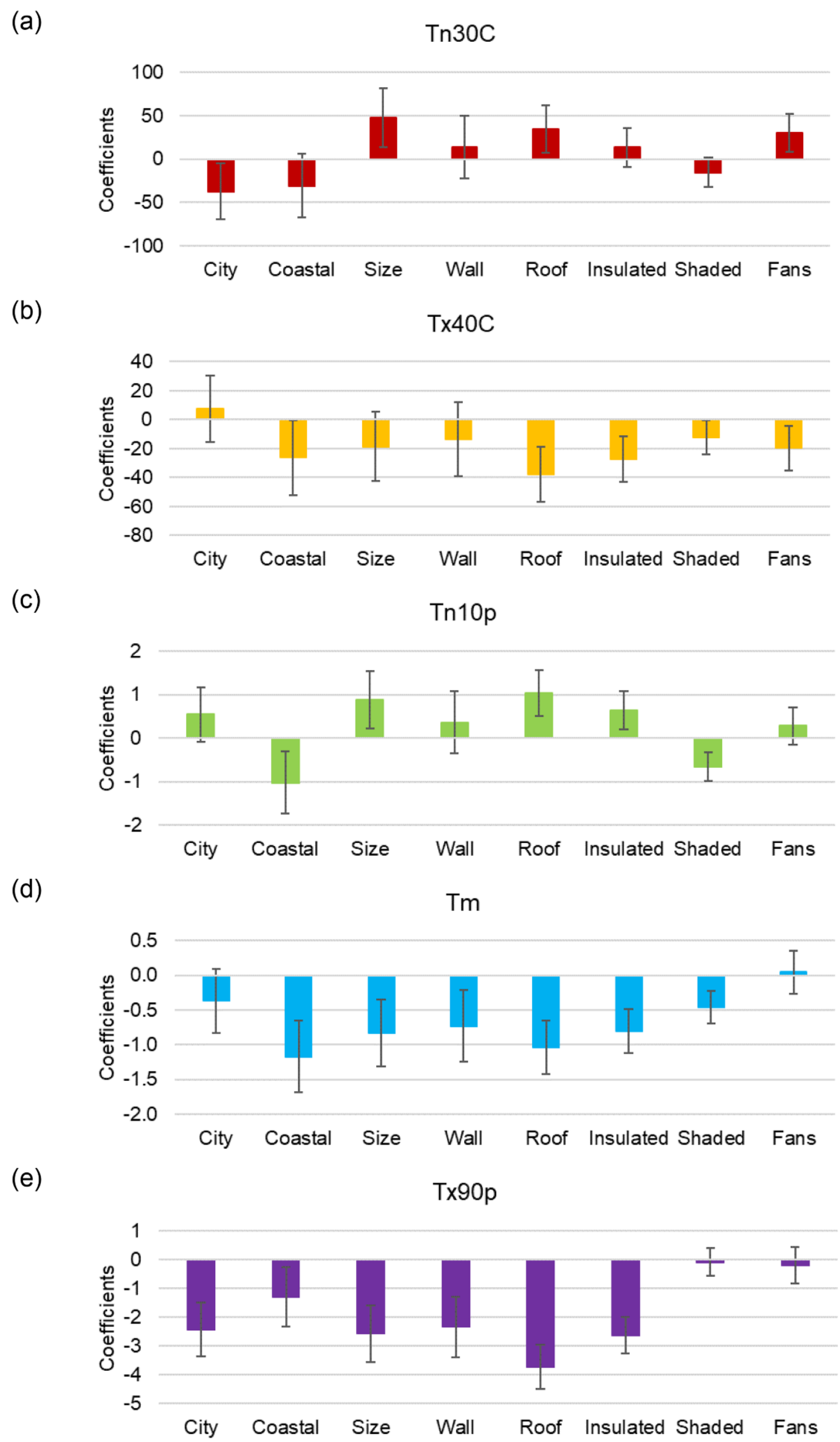

Figure 5. Coefficients for variables (horizontal axes) used in dummy regression models of: (a) number of hot nights (Tn30C); (b) number of very hot days (Tx40C); (c) 10th percentile of daily minimum temperature (Tn10p); (d) mean daily temperature (Tm); and (e) 90th percentile of the daily maximum temperature (Tx90p). See table S2 for model details. T-bars denote the standard error of coefficient estimates.

of low-income communities. Here, we consider the wider implications of our research for other parts of the Global South.

We show that conventional dry-bulb air temperature measurements at meteorological stations significantly under-report the extraordinary indoor temperatures faced by some households; yet such station data (or gridded derivatives) are routinely used as reference points for heatwave forecasts and climate change studies (e.g. Alexander *et al* 2006, Donat *et al*

2013, Raymond *et al* 2020). This adds to the sense that heatwave impacts are being overlooked for sub-Saharan Africa (Harrington and Otto 2020). Sub-hourly, indoor temperature data reveal that residents may be living much closer to a 'thermal precipice' than conventional ambient air temperature measurements suggest (Kenney *et al* 2004). We suspect that this situation is not unique to Ghana.

Although often used, we show that *mean* indoor temperature data can hide important trade-offs. For example, thatch with insulated ceilings has relatively low indoor Tx but comparatively high Tn. If the aim is to bring respite from high indoor Tx, preferred options are ceiling insulation, tree shade, and/or thatch roof materials. If improved sleeping conditions at night are the priority (i.e. lower Tn), then uninsulated metal roofs and/or tree shade are desirable. Such measures can reduce the frequency of very hot nights by 30 per year. This means that the diel temperature regime must be considered when evaluating heatwave impacts and adaptations.

There are also important considerations about the cultural and practical aspects of some modifications in high-density urban contexts (Satterthwaite *et al* 2018). For instance, concerns about security, pests, or poor air quality may discourage use of natural ventilation. Even though tree shade reduces insolation, this option is not always feasible within the dense urban fabric of informal settlements. Saplings may also struggle to establish in extreme hot-arid conditions. Furthermore, there are taboos against tree-planting amongst some communities in northern Ghana. Although such beliefs are waning (Hansen *et al* 2012), the matter was raised by several households in our study and may act as a deterrent.

The benefits of some building modifications appear modest when expressed as mean temperature changes. For example, tree shade reduces Tm by just 0.5 °C, yet the average frequency of very hot days (Tx40C) (as an indicator of potentially dangerous conditions) is reduced by 12 d per year (table S2). Benefits may also be framed as the amount of climate change that is countered, or the equivalent time delay for a given rise in temperature. For example, insulating a metal roof in Tamale (figure 1(e)) could reduce indoor Tx90p by 2.6 °C, effectively negating an outdoor temperature rise of 4.2 °C (figure S4(c)). This is the median warming by 2100 projected by the CMIP5 ensemble for the hot season in Ghana under RCP8.5 emissions (IPCC 2013). Hence, we advise the use of multiple temperature indices (as in table 2) when evaluating the impact of adaptation(s) to buildings.

We demonstrate how empirical data and statistical models can be used to evaluate building features and measures that are widely deployed by households in Ghana. However, other options, such as cool paint, more passive ventilation, increased ceiling height and increased wall thickness need to be tested (Santamouris 2014, Akbari and Kolokotsa 2016, Kolokotroni *et al* 2018). The influence of floor level on temperatures (inside multi-storey homes) and long-term trends in preference for certain materials are also worthy of further exploration. In our sample, ceiling insulation was present in 74% of the rooms. Amongst these, 69% used plywood, 20% PVC cladding or plastic sheeting, and 11% plaster. More widespread use of PVC tongue and groove panels in place of plywood would favour higher night-time indoor temperatures over the long-term (Naicker *et al* 2017).

We acknowledge that the benefits of fans are difficult to quantify without accompanying information about their use. Nonetheless, it is accepted that the protective value of fans is via increased airflow and evaporative cooling from sweating. Previous research shows that indoor fan use is beneficial up to ∼45 °C and 10% relative humidity or ∼40 °C and 60% relative humidity; beyond these limits there is increased risk of dehydration (Jay *et al* 2015). Some recommend against use of fans in very hot (⩾45 °C) and arid (<10% relative humidity) regions (Morris *et al* 2019)—conditions that are already approached during heatwaves in some parts of sub-Saharan Africa. Moreover, electricity supplies, and hence access to fan cooling, can be curtailed during heatwaves (Gough *et al* 2019, Kayaga *et al* 2020) while power networks feeding cooling systems may be damaged by cyclones, increasing the risk of deadly heat during blackouts (Matthews *et al* 2019). Hence, solutions should be both energy efficient and resilient to extreme weather.

Measures taken by many individual households to moderate indoor temperatures could also affect the intensity of the local urban heat island, when aggregated at community scales. For instance, cool paints and more reflective materials reduce the overall heat load to the urban environment (Kyriakodis and Santamouris 2018). Experiments with a house in Ghana showed that cool paint applied to a poorly insulated roof reduced the surface temperature by 7.8 °C and ceiling temperature by 6.2 °C during the hottest month (Kolokotroni *et al* 2018). Other studies show that green spaces, roofs, facades and walls also contribute to reduced intensity of the daytime UHI (for a review see: Akbari and Kolokotsa 2016). In turn, lower outdoor temperatures may also have indirect benefits by reducing energy consumption for space cooling (Mastrucci *et al* 2019).

Finally, we quantified the benefits of selected modifications but the socio-ecological-technological dimensions of adapting to extreme heat should not be overlooked (Markolf *et al* 2018). These include the social acceptability of measures, such as tree-planting, or preference for modern materials over traditional. Heat avoidance behaviours, including outdoor sleeping and other night-time activities, such as socializing, night school, household chores, and small-scale economic activity significantly increase malaria risk (Monroe *et al* 2015). Consequently, there is a strong imperative to moderate indoor temperature extremes at night as well as during the day. Since most home-based livelihood activities take place outside the physical structure of the home, in a kiosk or under an adjacent veranda (Gough 2010, Amankwaa *et al* 2017), measures are also needed for reducing ambient heat in outdoor spaces.

5. Conclusions

This study exposes the level to which observations at meteorological stations and use of daily means under-report the extraordinary indoor temperatures encountered by some households. Our data also show the relative effects of building location, size, wall/roof materials, insulation, shade, and cooling systems on extreme indoor temperatures. We used statistical modelling to quantify the benefits of affordable adaptation measures (traditional roof materials, ceiling insulation, shading by vegetation, and electric fans). Critical trade-offs emerge when evaluating consequences of these measures using more nuanced temperature indices. Such evidence is urgently needed to properly monitor and then guide modifications to low-income housing. In this way, vulnerable people in tropical cities will have an opportunity to become more resilient to climate change.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

Ahmadalipour A, Moradkhani H and Kumar M 2019 Mortality risk from heat stress expected to hit poorest nations the hardest *Clim. Change* **152** 569–79

Akbari H and Kolokotsa D 2016 Three decades of urban heat islands and mitigation technologies research *Energy Build.* **133** 834–42

Alexander L V *et al* 2006 Global observed changes in daily climate extremes of temperature and precipitation *J. Geophys. Res. Atmos.* **111** D05109

Amankwaa E F 2017 Water and electricity access for home-based enterprises and poverty reduction in the greater Accra metropolitan area (GAMA), Ghana PhD Thesis University of Ghana

Amos-Abanyie S, Akuffo F O and Kutin-Sanwu V 2013 Effects of thermal mass, window size, and night-time ventilation on peak indoor air temperature in the warm-humid climate of Ghana *Sci. World J.* **2013** 620195

Ayanlade A, Esho O M, Popoola K O, Jeje O D and Orola B A 2019 Thermal condition and heat exposure within buildings: a case study of tropical city *Case Stud. Therm. Eng.* **14** 100477

Codjoe S N A *et al* 2020 Impact of extreme weather conditions on healthcare provision in urban Ghana *Soc. Sci. Med.* **258** 113072

Coffel E, Horton R M and De Sherbinin A M 2017 Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century *Environ. Res. Lett.* **13** 014001

Dapi L N, Rocklöv J, Nguefack-Tsague G, Tetanye E and Kjellstrom T 2010 Heat impact on schoolchildren in Cameroon, Africa: potential health threat from climate change *Glob. Health Action* **3** 5610

Dauda A M and Gao H 2013 Improving sustainability of housing in Ghana through energy efficient climate control strategies *Adv. Mater. Res.* **608** 1698–704

Dodman D, Archer D and Satterthwaite D 2019 Editorial: responding to climate change in contexts of urban poverty and informality *Environ. Urban* **31** 3–12

Donat M G, Alexander L V, Yang H, Durre I, Vose R and Caesar J 2013 Global land-based datasets for monitoring climatic extremes *Bull. Am. Meteorol. Soc.* **94** 997–1006

Dong W, Liu Z, Liao H and Tang Q 2015 New climate and socio-economic scenarios for assessing global human health challenges due to heat risk *Clim. Change* **130** 505–18

Dunne J P, Stouffer R J and John J G 2013 Reductions in labour capacity from heat stress under climate warming *Nat. Clim. Change* **3** 563–6

Gemini Data Loggers 2015 Tinytag transit 2 temperature data logger (−40 to +70 °C) TG-4080 (available at: http://gemini2.assets.d3r.com/pdfs/original/2081-tg-4080.pdf) (Accessed 6 March 2015)

Giridharan R and Emmanuel R 2018 The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: a review *Sustain. Cities Society* **40** 677–87

Gough K V 2010 Continuity and adaptability of home-based enterprises: a longitudinal study from Accra, Ghana *Int. Dev. Plan. Rev.* **32** 45–70

Gough K V, Yankson P W K, Wilby R L, Amankwaa E, Abarike M, Codjoe S, Griffiths P, Kaba C, Kasei R and Kayaga S 2019 Vulnerability to extreme weather events in cities:

implications for infrastructure and livelihoods *J. Br. Acad.* **7** 155–81
Hansen N T, Ræbild A and Hansen H H 2012 Management of trees in northern Ghana—when the approach of development organizations contradicts local practices *For. Trees Livelihoods* **21** 241–52
Harrington L J and Otto F E 2020 Reconciling theory with the reality of African heatwaves *Nat. Clim. Change* **10** 796–8
Holmes S H, Phillips T and Wilson A 2016 Overheating and passive habitability: indoor health and heat indices *Build. Res. Inform.* **44** 1–19
IPCC 2013 Annex I: atlas of global and regional climate projections ed G J van Oldenborgh, M Collins, J Arblaster, J H Christensen, J Marotzke, S B Power, M Rummukainen and T Zhou *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker, D Qin, G K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley (Cambridge: Cambridge University Press)
Jagarnath M, Thambiran T and Gebreslasie M 2020 Heat stress risk and vulnerability under climate change in Durban metropolitan, South Africa—identifying urban planning priorities for adaptation *Clim. Change* **163** 807–29
Jay O, Cramer M N, Ravanelli N M and Hodder S G 2015 Should electric fans be used during a heat wave? *Appl. Ergon.* **46** 137–43
Kayaga S *et al* 2020 Cities and extreme weather events: impact of flooding and extreme heat on water and electricity services in Ghana *Environ. Urban* (https://doi.org/10.1177/0956247820952030)
Kenney W L, Degroot D W and Holowatz L A 2004 Extremes of human heat tolerance: life at the precipice of thermoregulatory failure *J. Therm. Biol.* **29** 479–85
Kolokotroni M, Shittu E, Santos T, Ramowski L, Mollard A, Rowe K, Wilson E, de Brito Filho J P and Novieto D 2018 Cool roofs: high tech low cost solution for energy efficiency and thermal comfort in low rise low income houses in high solar radiation countries *Energy Build.* **176** 58–70
Kyriakodis G E and Santamouris M 2018 Using reflective pavements to mitigate urban heat island in warm climates-results from a large scale urban mitigation project *Urban Clim.* **24** 326–39
Li D, Yuan J and Kopp R B 2020 Escalating global exposure to compound heat-humidity extremes with warming *Environ. Res. Lett.* **15** 064003
Makaka G and Meyer E 2006 Temperature stability of traditional and low-cost modern housing in the Eastern Cape, South Africa *J. Build. Phys.* **30** 71–86
Maller C J and Strengers Y 2011 Housing, heat stress and health in a changing climate: promoting the adaptive capacity of vulnerable households, a suggested way forward *Health Promot. Int.* **26** 492–8
Markolf S A, Chester M V, Eisenberg D A, Iwaniec D M, Davidson C I, Zimmerman R, Miller T R, Ruddell B L and Chang H 2018 Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience *Earth's Future* **6** 1638–59
Mastrucci A, Byers E, Pachauri S and Rao N D 2019 Improving the SDG energy poverty targets: residential cooling needs in the global South *Energy Build.* **186** 405–15
Matthews T, Wilby R L and Murphy C 2017 Communicating the deadly consequences of global warming for human heat stress *Proc. Natl Acad. Sci.* **114** 3861–6
Matthews T, Wilby R L and Murphy C 2019 An emerging tropical cyclone-deadly heat compound hazard *Nat. Clim. Change* **9** 602–6
Monroe A, Asamoah O, Lam Y, Koenker H, Psychas P, Lynch M, Ricotta E, Hornston S, Berman A and Harvey S A 2015 Outdoor-sleeping and other night-time activities in northern Ghana: implications for residual transmission and malaria prevention *Malaria J.* **14** 35
Mora C *et al* 2017 Global risk of deadly heat *Nat. Clim. Change* **7** 501–6
Morakinyo T E, Dahanayake K K C, Adegun O B and Balogun A A 2016 Modelling the effect of tree-shading on summer indoor and outdoor thermal condition of two similar buildings in a Nigerian university *Energy Build.* **130** 721–32
Morris N B, English T, Hospers L, Capon A and Jay O 2019 The effects of electric fan use under differing resting heat index conditions: a clinical trial *Ann. Intern. Med.* **171** 675–7
Naicker N, Teare J, Balakrishna Y, Wright C Y and Mathee A 2017 Indoor temperatures in low cost housing in Johannesburg, South Africa *Int. J. Environ. Res. Public Health* **14** 1410
Nangombe S, Zhou T, Zhang W, Wu B, Hu S, Zou L and Li D 2018 Record-breaking climate extremes in Africa under stabilized 1.5 C and 2 C global warming scenarios *Nat. Clim. Change* **8** 375–80
Nematchoua M K, Ricciardi P, Reiter S, Asadi S and Demers C M 2017 Thermal comfort and comparison of some parameters coming from hospitals and shopping centers under natural ventilation: the case of Madagascar Island *J. Build. Eng.* **13** 196–206
Nematchoua M K, Tchinda R, Ricciardi P and Djongyang N 2014 A field study on thermal comfort in naturally-ventilated buildings located in the equatorial climatic region of Cameroon *Ren. Sustain. Energy Rev.* **39** 381–93
Nguyen J L and Dockery D W 2016 Daily indoor-to-outdoor temperature and humidity relationships: a sample across seasons and diverse climatic regions *Int. J. Biometeorol.* **60** 221–9
Ojeh V N, Balogun A A and Okhimamhe A A 2016 Urban-rural temperature differences in Lagos *Climate* **4** 29
Oleson K W, Monaghan A, Wilhelmi O, Barlage M, Brunsell N, Feddema J, Hu L and Steinhoff D F 2015 Interactions between urbanization, heat stress, and climate change *Clim. Change* **129** 525–41
Parkes B, Cronin J, Dessens O and Sultan B 2019 Climate change in Africa: costs of mitigating heat stress *Clim. Change* **154** 461–76
Quinn A, Tamerius J D, Perzanowski M, Jacobson J S, Goldstein I, Acosta L and Shaman J 2014 Predicting indoor heat exposure risk during extreme heat events *Sci. Total Environ.* **490** 686–93
Raymond C, Matthews T and Horton R M 2020 The emergence of heat and humidity too severe for human tolerance *Sci. Adv.* **6** eaaw1838
Ringard J *et al* 2016 The intensification of thermal extremes in west Africa *Glob. Planet. Change* **139** 66–77
Rohat G, Flacke J, Dosio A, Dao H and van Maarseveen M 2019 Projections of human exposure to dangerous heat in African cities under multiple socioeconomic and climate scenarios *Earth's Future* **7** 528–46
Santamouris M 2014 Cooling the cities–a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments *Sol. Energy* **103** 682–703
Satterthwaite D, Archer D, Colenbrander S, Dodman D, Hardoy J and Patel S 2018 Responding to climate change in cities and in their informal settlements and economies. IIED paper prepared from the IPCC *Int. Scientific Conf. Cities and Climate Change* (*Edmonton*, *2018*) (Accessed 4 December 2019)
Scott A A *et al* 2017 Temperature and heat in informal settlements in Nairobi *PLoS One* **12** e0187300
Sillmann J, Kharin V V, Zhang X, Zwiers F W and Bronaugh D 2013 Climate extremes indices in the CMIP5 multimodel ensemble: part 1. model evaluation in the present climate *J. Geophys. Res. Atmos.* **118** 1716–33
Simwanda M, Ranagalage M, Estoque R C and Murayama Y 2019 Spatial analysis of surface urban heat islands in four rapidly growing African cities *Remote Sens.* **11** 1645
Taylor P B, Mathews E H, Kleingeld M and Taljaard G W 2000 The effect of ceiling insulation on indoor comfort *Build. Environ.* **35** 339–46

Testo 2020 Test 610 humidity/temperature measuring instrument Data sheet (available at: https://static-int.testo.com/media/48/db/71587df6c7c4/testo-610-Data-sheet.pdf)

White-Newsome J L, Sánchez B N, Jolliet O, Zhang Z, Parker E A, Dvonch J T and O'Neill M S 2012 Climate change and health: indoor heat exposure in vulnerable populations *Environ. Res.* **112** 20–27

Wilby R L 2007 A review of climate change impacts on the built environment *Built. Environ. J.* **33** 31–45

Wright C Y, Street R A, Cele N, Kunene Z, Balakrishna Y, Albers P N and Mathee A 2017 Indoor temperatures in patient waiting rooms in eight rural primary health care centers in Northern South Africa and the related potential risks to human health and wellbeing *Int. J. Environ. Res. Public Health* **14** 43

Zhao Y, Ducharne A, Sultan B, Braconnot P and Vautard R 2015 Estimating heat stress from climate-based indicators: present-day biases and future spreads in the CMIP5 global climate model ensemble *Environ. Res. Lett.* **10** 084013